

Superluminal neutrinos and domain walls

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Abstract

In this letter, we propose that the recent measurement of superluminal neutrinos in OPERA could be explained by the existence of a domain wall which is left behind after the phase transition of some scalar field in the universe. The scalar field couples to the neutrino and photon field with different effective couplings. It causes different effective metrics and the emergence of superluminal neutrinos. Moreover, if the supernova and the earth are in the same plane parallel to the wall, or the thickness of the wall is much smaller than the distance from the supernova to the earth, the contradiction between OPERA and SN1987a can be reconciled.

Recently OPERA collaboration [1] published their results which show that the muon neutrino moves faster than the speed of light (c). The ν_μ arrives at the Gran Sasso laboratory from CERN by 60 ns earlier than the photon, with a distance around 730 km. The beam of ν_μ has mean energy 17 GeV. The measured relative amount of the superluminal velocity is:

$$\frac{v_\nu - c}{c} = (2.48 \pm 0.28(\text{stat}) \pm 0.30(\text{sys})) \times 10^{-5}, \quad (1)$$

with a statistical significance of 6.0σ . Many theoretical explanations have been proposed immediately, respecting or violating Lorentz invariance [2]. While as early as in 2005, there were discussions on the possibility of superluminal neutrinos [3].

As one of the cornerstones of special relativity, the constancy of speed of light is from the lessons in electromagnetic theory. It is reasonable that all the participants of $U(1)$ gauge interaction respect the speed limit c . However, since neutrinos only play roles in weak and gravitational interactions, there exit possibilities of superluminal propagation. This property serves as an ingredient of the $SU(2)$ symmetry breaking.

In this letter, we propose a domain wall model explicitly breaking the $SU(2)$ symmetry while spontaneously breaking Lorentz invariance. In the literature, there are discussions on variation of the light speed caused by domain walls (brane-worlds) [4]. In a companion paper, we address the possible influences on superluminal neutrinos from two other topological defects, cosmic strings and monopoles [5]. To simplify the story, only a real scalar field ϕ , responsible to generate a domain wall where we live, a Dirac neutrino field ψ and the photon field A_μ are included in the model. We also assume the neutrino is massless since its mass is very tiny compared to the its energy. Since the gravitational

field is very weak around the earth it is safe to consider our model in Minkowski space. The effective Lagrangian is given by

$$\begin{aligned} \mathcal{L} = & i\bar{\psi}\gamma^\mu\partial_\mu\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{4}\lambda(\phi^2 - \sigma^2)^2 \\ & + \frac{ig}{M^4}\bar{\psi}\gamma_\mu\partial_\nu\psi\partial^\mu\phi\partial^\nu\phi - \frac{g'}{8M^4}\partial^\mu\phi\partial^\nu\phi F_{\mu\rho}F_\nu^\rho + \dots, \end{aligned} \quad (2)$$

where M is the mass scale where new physics arise. g and g' are the couplings for the effective operators with the order of unity in the absence of fine tuning in the new physics. Z_2 symmetry is imposed on the Lagrangian in the construction of the effective operators. Therefore, the lower dimensional operators, $\bar{\psi}\gamma_\mu D_\nu\psi\partial^\mu\partial^\nu\phi$ and $\partial^\mu\partial^\nu\phi F_{\mu\rho}F_\nu^\rho$ are excluded in the effective Lagrangian due to the Z_2 symmetry. The two eight dimensional operators in the second line of eqn. (2) are the lowest dimensional operators which are relevant to modifying the kinetic terms of neutrino and photon fields. \dots are either irrelevant effective operators or higher dimensional operators. i is put in front of g to make g real.

After the big bang, the scalar field ϕ is assumed to go through phase transition from the symmetric phase $\phi = 0$ to the broken one $\phi = \pm\sigma$. The Kibble mechanism [6] tells us that productions of various topological effects, such as domain walls, cosmic strings and magnetic monopoles, are unavoidable in the early universe. Suppose there is a domain wall produced by a scalar field around our earth. The wall is located in the xy plane at $z = 0$. The profile of the domain wall

$$\phi_w(z) = \sigma \tanh\left(\frac{z}{\Delta}\right), \quad (3)$$

is determined by the equation of motion for ϕ with boundary conditions $\phi_w(\pm\infty) = \pm\sigma$. $\Delta = \left(\frac{\lambda}{2}\right)^{-\frac{1}{2}}\sigma^{-1}$ characterizes the thickness of the wall.

Since the wall is around the earth, its existence effectively modifies the neutrino's kinetic term as

$$i\left(\eta_{\mu\nu} + \frac{g}{M^4}\partial^\mu\phi_w\partial^\nu\phi_w\right)\bar{\psi}\gamma_\mu\partial_\nu\psi. \quad (4)$$

Therefore, the equation of motion for ψ is

$$\left(\eta_{\mu\nu} + \frac{g}{M^4}\partial^\mu\phi_w\partial^\nu\phi_w\right)\gamma_\mu\partial_\nu\psi + \dots = 0, \quad (5)$$

where \dots are terms involving $\tilde{\phi} = \phi - \phi_w$ and have no relevance to our discussion. With the help of eqn. (3), the effective metric the neutrino see is

$$ds^2 = -dt^2 + dx^2 + dy^2 + \left(1 + \frac{g\sigma^2}{M^4\Delta^2\cosh^4\left(\frac{z}{\Delta}\right)}\right)dz^2. \quad (6)$$

It is interesting to note that the effective light cone for the neutrino get modified in z -direction only. It indicates that the massless neutrino travels at the same speed of light in x - and y -directions, while in z -direction the neutrino travels faster than light due to the existence of the factor $\frac{g\sigma^2}{M^4\Delta^2\cosh^4\left(\frac{z}{\Delta}\right)}$.

In order to put the strictest lower bound on $\frac{g\sigma^2}{M^4\Delta^2}$, we consider a neutrino traveling from (x, y, z_i) to (x, y, z_f) along z -direction. In this situation, the domain wall causes the greatest deviation between the speed of a neutrino and that of light. In this scenario, the time for the neutrino to travel from (x, y, z_i) to (x, y, z_f) is simply given by

$$t_\nu = \int_{z_i}^{z_f} \sqrt{1 + \frac{g\sigma^2}{M^4\Delta^2\cosh^4\left(\frac{z}{\Delta}\right)}} dz \quad (7)$$

$$\begin{aligned}
&\approx \int_{z_i}^{z_f} \left(1 + \frac{g\sigma^2}{2M^4\Delta^2 \cosh^4\left(\frac{z}{\Delta}\right)} \right) dz \\
&= (z_f - z_i) + \frac{g\sigma^2}{6M^4\Delta} \left(f\left(\frac{z_f}{\Delta}\right) - f\left(\frac{z_i}{\Delta}\right) \right),
\end{aligned}$$

where $f(z) = \left(2 + \frac{1}{\cosh^2(z)}\right) \tanh(z)$. It is expected, as we will show later, that $\frac{g\sigma^2}{M^4\Delta^2} \ll 1$ as a consequence of $\delta = \frac{v_\nu - c}{c} \sim 10^{-5}$ measured in OPERA. Thus higher order terms of $\left(\frac{g\sigma^2}{M^4\Delta^2}\right)$ in the second line of the above equation are discarded.

Parallel to the neutrino calculation, the photon field also undergoes an effective metric produced by the effective Lagrangian. It is straightforward to write down the effective metric as

$$ds^2 = -dt^2 + dx^2 + dy^2 + \left(1 + \frac{g'\sigma^2}{M^4\Delta^2 \cosh^4\left(\frac{z}{\Delta}\right)} \right) dz^2.$$

The time for a photon traveling from (x, y, z_i) to (x, y, z_f) is

$$t_c \approx (z_f - z_i) + \frac{g'\sigma^2}{6M^4\Delta} \left(f\left(\frac{z_f}{\Delta}\right) - f\left(\frac{z_i}{\Delta}\right) \right).$$

The relative difference of the neutrino speed with respect to the speed of light is

$$\delta = \frac{v_\nu - c}{c} = \frac{t_c - t_\nu}{t_\nu} \approx \frac{(g' - g)\sigma^2}{6M^4\Delta^2} \frac{f\left(\frac{z_f}{\Delta}\right) - f\left(\frac{z_i}{\Delta}\right)}{\frac{z_f}{\Delta} - \frac{z_i}{\Delta}}. \quad (8)$$

$f(z)$ is a monotonically increasing function so δ is always positive as long as $g < g'$. The effective couplings g and g' are determined by the new physics beyond M . If there is no symmetry or fine-tuning in the new physics regime, g , g' and $g - g'$ should be the order of unity.

It is subtle to calculate physical distances in any experiment since different fields see different effective metrics in our model. Specifically, the way the coordinates z_f and z_i related to physical distances measured in various experiments, such as OPERA or SN1987a, depends on the kind of fields employed in the measurements of physical distances. The neutrino baseline length in OPERA is obtained by analyzing the GPS benchmark positions. The distance to SN1987a is calculated using the observed angular size of it rings [7]. Thus in both experiments the photon's effective metric have been used to calculate physical distances. However, the differences between physical distances and $|z_f - z_i|$ are $\mathcal{O}\left(\frac{\sigma^2}{M^4\Delta^2}\right)$ if g' is the order of unity. Only keeping the leading order terms in δ , one can simply treat $|z_f - z_i|$ as physical distances in the following discussion.

Nonzero δ can be used to determine $\frac{(g' - g)\sigma^2}{M^4\Delta^2}$ as long as z_i and z_f are known. In order to explain OPERA results, $\frac{f(z_f^{\text{OPERA}}/\Delta) - f(z_i^{\text{OPERA}}/\Delta)}{z_f^{\text{OPERA}}/\Delta - z_i^{\text{OPERA}}/\Delta}$ ought to be the order of unity. It means that z_f^{OPERA} and z_i^{OPERA} have to be in the range of $(-\Delta, \Delta)$. The global maximum of $(f(\frac{z_f}{\Delta}) - f(\frac{z_i}{\Delta})) / (\frac{z_f}{\Delta} - \frac{z_i}{\Delta})$, which is 3, is achieved as $z_f \rightarrow z_i = 0$. Hence the measurement of δ can be used to put a lower bound on $\frac{\sigma^2}{M^4\Delta^2}$ even without detailed knowledge of z_i and z_f . The measurements δ_{OPERA} in OPERA implies

$$\frac{(g' - g)\sigma^2}{M^4\Delta^2} \sim \frac{\sigma^2}{M^4\Delta^2} \gtrsim 10^{-5}, \quad (9)$$

where the fact that $g' - g$ is the order of unity in the absence of fine-tuning has been used.

It is interesting to ask what is the thickness of the domain wall Δ provided its existence could explain OPERA results. Three possibilities for Δ are proposed as follow,

1. The peculiar velocity of the domain wall is zero. The peculiar velocity of the sun with respect to distant galaxies is estimated to be $\sim 400\text{km/sec}$ [8]. The data of superluminal neutrinos have been taken from 2009 to 2011 in OPERA. During the period, the sun travelled $3.8 \times 10^{10} \text{ km} \sim 10^{-3} \text{ ly}$. In order to explain the superluminal neutrinos in our model, the thickness of domain wall Δ has to be larger than 10^{-3} ly .
2. The domain wall happens to travel with the sun. The wall should be big enough to hold the orbit of the earth around the sun. The distance between the sun and the earth is $1.5 \times 10^8 \text{ km} \sim 10^{-5} \text{ ly}$. Thus Δ has to be larger than 10^{-5} ly .
3. The domain wall happens to travel with the earth. In this case, Δ has to be greater than the scale of the earth $\sim 10^4 \text{ km} \sim 10^{-9} \text{ ly}$.

On the other hand, measurements from SN1987A found $\delta_{\text{SN}} = \frac{v_{\nu}-c}{c} < 2 \times 10^{-9}$ [9], much smaller than δ_{OPERA} obtained in OPERA. In order to explain the obvious contradiction, two possible scenarios are discussed below.

1. The supernova lies in the same xy plane as the earth. In this scenario, both neutrino and photon travel in xy plane with the same speed. Careful analysis of the supernova's position and the direction of the baseline in OPERA has to be carried out to check the possibility of this scenario.
2. The supernova and the earth are not in the same xy plane. By assuming the supernova is on z -axis, the distance from SN1987a to the earth $L_{\text{SN}} \approx |z_f^{\text{SN}} - z_i^{\text{SN}}| \sim 1.6 \times 10^6 \text{ ly}$. z_f^{SN} is the position of the supernova and $z_i^{\text{SN}} \approx z_i^{\text{OPERA}}$ as long as Δ is larger than the scale of the earth. Thus eqn. (8) yields

$$\delta_{\text{SN}} \sim \delta_{\text{OPERA}} \frac{\left| f\left(\frac{z_f^{\text{SN}}}{\Delta}\right) - f\left(\frac{z_i^{\text{SN}}}{\Delta}\right) \right|}{\frac{L_{\text{SN}}}{\Delta}} \sim \delta_{\text{OPERA}} \frac{\Delta}{L_{\text{SN}}}, \quad (10)$$

where $\delta_{\text{OPERA}} \sim \frac{\sigma^2}{M^4 \Delta^2}$ and $\left| f\left(\frac{L_{\text{SN}}}{\Delta}\right) \right| \leq 2$ have been used. The results from OPERA and SN1987a give $\delta_{\text{SN}}/\delta_{\text{OPERA}} \lesssim 10^{-4}$. It implies $\Delta/L_{\text{SN}} \lesssim 10^{-4}$ and $\Delta \lesssim 10^2 \text{ ly}$.

Finally, for sake of convenience, the neutrino baseline is assumed along z -axis in this letter. However, taking into account the rotation and revolution of the earth, this is not the case in OPERA experiments. If one is only interested in order of magnitudes, the above simplification is guaranteed. Measurements of dependencies of δ_{OPERA} on the direction of the baseline in future experiments could confirm or rule out our proposed model.

In conclusion, we discussed that existence of a domain wall could explain the recent measurement of superluminal neutrinos in OPERA. We assumed that the earth lives in a domain wall and the corresponding scalar couples to the neutrino as well as photon fields through the effective operators in eqn. (2). Once eqn. (9) is satisfied, the observed δ_{OPERA} could be explained in the framework. Furthermore, two scenarios have been proposed to reconcile OPERA with SN1987a. In one scenario, the supernova and the earth lie in the same xy plane parallel to the domain wall. Hence neutrinos and photons travel at the same speed toward the earth after the explosion. In the other scenario, the thickness of the domain wall is much smaller than the distance between the supernova and the earth. Then eqn. (8) yields $\delta_{\text{SN}} \ll \delta_{\text{OPERA}}$.

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